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District Cooling System with Solar based Vapor Absorption Chiller: A Techno-economic Case Study

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Abstract**—** A solar-based vapour absorption machine (VAM) chiller-based district cooling system (DCS) has been designed and its financials have been worked out in the context of a high-rise 80 apartment tower. Comparisons have been made with a vapour compression refrigeration (VCR) based DCS, and with the existing system of 3 unitary split air conditioning units per apartment. The solar VAM DCS carbon footprint is 75% and 78 % smaller than VCR DCS and unitary system. While the capital cost is 58 % larger than VCR DCS, the operating costs are 63 % lower. The VAM-based DCS, though practically complex, has the potential for substantial carbon savings which is needed to slow down carbon emissions.

Keywords— District cooling system, Vapor absorption machine, solar collector, Cooling demand, Carbon footprint.

I. INTRODUCTION

In urban areas in India during hot climates about 40 % of electric power consumption is by air conditioners which are vapour compression refrigeration (VCR) based and unitary units. Large single-customer installations use central AC systems using variable flow refrigeration, or chilled water systems that are more efficient. In this paper we explore the district cooling system (DCS) for hot climates to provide cooling in apartments. The vapour absorption machine (VAM)-based system accomplishes the compression by pumping a water-salt mixture thereby consuming far less electricity. However, it needs a source of heat which in this case is solar heaters with gas or other renewable fuel fired boiler for exigencies.

II. SOLAR-BASED VAM DCS FEATURES

A. *Technical scheme*

A District Cooling System (DCS) caters to the cooling requirements of a geographical area and has many clients who are billed individually for their consumption; a schematic is shown in Figure 1 where a central chiller plant supplies piped chilled water to the end-users and takes back the warm water. Each user has one or more fan coil unit(s), FCUs, which cool the room air. The cooling energy for each customer is metered for billing purposes. Generally, DCS are much larger than that considered here and could also include clients like commercial buildings, hotels, schools, and independent bungalows.

The scheme of the solar-based VAM chiller for producing chilled water is shown in Figure 2. At the centre is the VAM chiller where water is the working fluid and LiBr is the absorbent. The absorber, heat exchanger and generator accomplish the task of compressing the working substance. The compressed hot vapour is condensed in the water circuit which is transferred to the air via the cooling tower. The condensed water is expanded to produce low temperature vapour. The low temperature vapour gets heated in the evaporator by cooling the water in the chilled water system. The generator is supplied with heat in the form of hot thermic fluid which is stored in a hot thermic fluid tank; this also serves as an energy storage device.

After passing through the generator, the cold thermic fluid id stored in the cold thermic fluid storage tank. In normal operation, the cold thermic fluid is heated in a series of parabolic trough type solar collectors and led to the hot thermic fluid tank. As a back-up to solar energy, an auxiliary boiler is provided whose fuel can be an oil or any renewable energy source like agricultural or municipal waste. The state points have been numbered on this diagram. The working substance pairs can be water with LiBr as the absorbent,or ammonia with water as absorbent.

B. *Related Studies*

Absorption chillers are a mature technology, are highly reliable, have high COP but their use in district cooling systems has been sparse [1]. District cooling systems are in

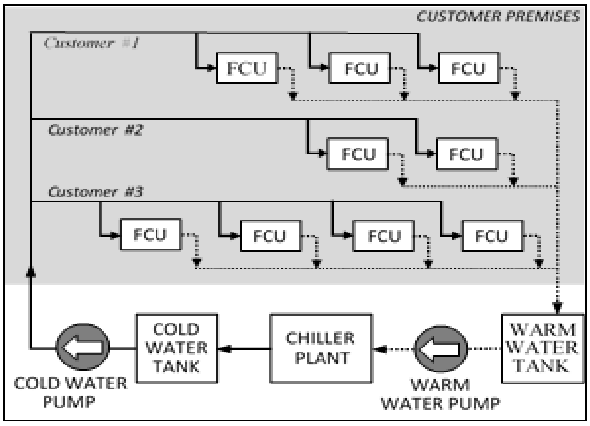

Figure 1 Schematic of a District Cooling System (DCS)

wide use in Qatar, Lima, Peru, Gavle, and Gandhinagar [2,3,4]; all these employ VCR type chillers and 30 % reduction in carbon footprint has been claimed [5].[6]. Energy conservation and thereby, carbon emission reduction with solar-based DCS system qualify for carbon credits. The average price of a carbon credit is \$2.4/tCO$_2$e, and countries like India and China have been taking advantage of this scheme by selling their credits to European countries [7, 8].

III. SYSTEM –DESIGN AND SIZING BASIS

A. Cooling Load Demand

Cooling demand of the residential units under consideration comprises of transmission, solar infiltration, sensible infiltration, latent infiltration, and internal loads.

Transmission load: The transmission cooling load arises due to temperature difference between indoor and outdoor air, and results in convection and conduction heat transfer through opaque surfaces, such as, roofs, and walls. It is given by $Q_T = UA_T(T_o - T_i)$, Q_T is transmission cooling load (kW), A_T is a total transmission area of the space, T_o is outside air temperature (°C), and T_i is inside air temperature (°C) and U is the overall heat transfer coefficient.

Solar infiltration load: Incoming solar radiation through open doors/windows and other fenestration area and is calculated as follows. Q_S, the solar infiltration load (kW) is $Q_S = SA_F D_{NI}$, where S is solar heat gain coefficient, A_F is total fenestration area (m^2), and D_{NI} is direct normal irradiation (W/m^2).

Sensible infiltration load: The sensible infiltration load results from air leakages into the air-conditioned space due to doors and windows and it is $Q_{SI} = MC_p(T_o - T_i)$, where, Q_{SI} is the sensible infiltration load (kW) , M is mass flow rate of air leakage into the space (kg/s), C_p is constant pressure specific heat of air $(1.005\ kJ/kgK)$. The leakage mass flow rate of air, M, depends on the number of air changes and is $M = \rho_A\ ACH\ (V/3600)$, where, ρ_A is density of air, ACH is air changes per hour for cooling space, V is volume of air-conditioned space which is the volume of building.

Latent infiltration load: The latent infiltration load is the load, $Q_{LI} = Mh_{fg}(W_o - W_i)$, occurs due to difference between indoor and outdoor specific humidity.

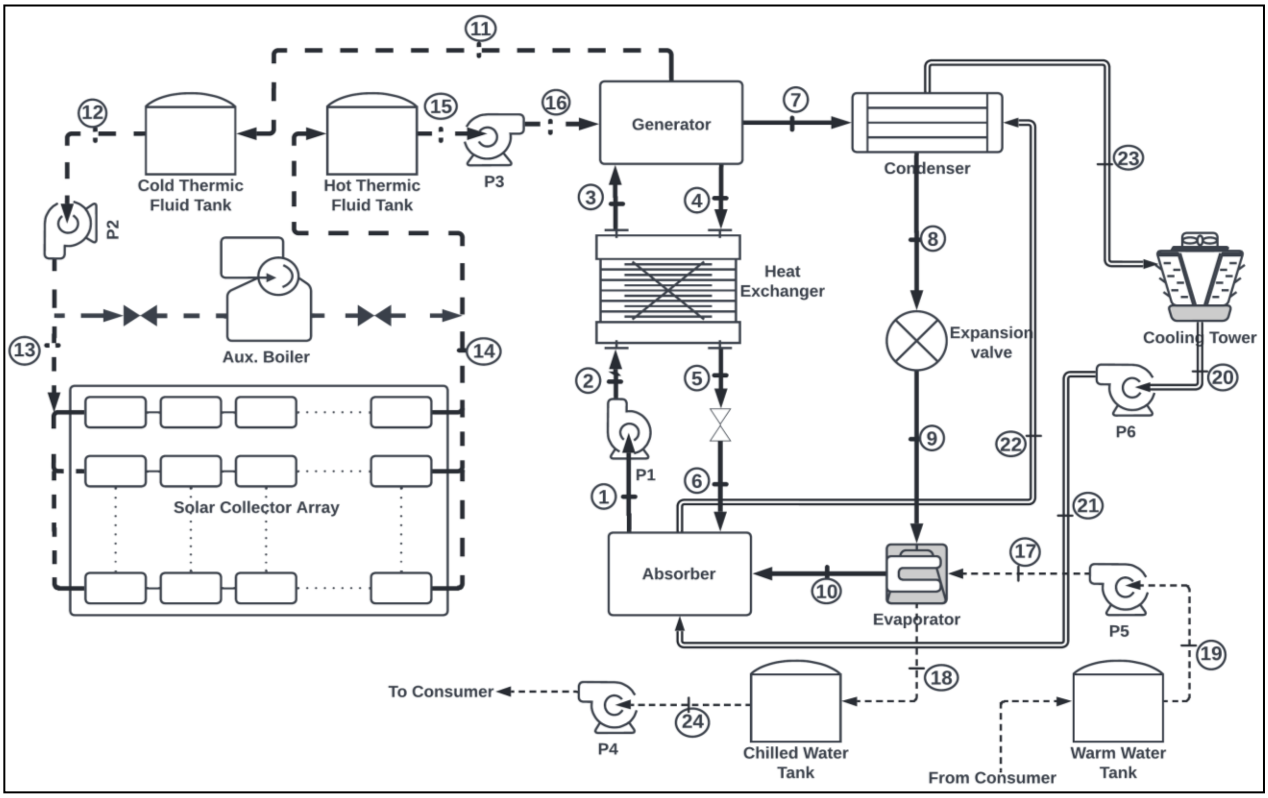

Figure 2 Integrated schematic of solar thermal powered VAM based DCS

It can be calculated as below. Here, h_{fg} is specific enthalpy of vaporization of water (kJ/kg), W_o is outdoor specific humidity ratio (kg/kg of dry air), and W_o is indoor specific humidity ratio (kg/kg of dry air). The outdoor specific humidity ratio is $W_o = 621.97\, P_W/(P_A - P_W)$; P_W and P_A are vapour pressure of water, and ambient pressure, respectively

Internal load: The internal load consists of the cooling load caused by heat input from various equipment and occupants of the space. For the reference building, the total internal load is calculated after assuming the occupancy, heat generation devices, etc. at 65 kW.

Total cooling load: The total cooling load for an air conditioning space includes all the components discussed above which will be used as a representative load for determining the capacities of system components, $Q_{Total} = Q_T + Q_S + Q_{SI} + Q_{LI} + Q_{IL}$

B. Solar Availability and Collector Effectiveness

The integrated approach to the solar-based VAM DCS depends on solar availability and climatic conditions which affect cooling demand. Solar irradiation varies on monthly and hourly basis and depends on the site location which in this study is Ahmedabad, India. At this location, the monthly maximum and minimum dry bulb temperature, DBT, and maximum solar irradiation for every month are shown in Figure 3 which determine the cooling demand.

Solar collector area is decided such that there is adequate thermal storage of hot thermic fluid 24 hour operation. Peaking cooling load is met by chilled water storage. The solar energy absorbed by the collectors from direct normal irradiation is as given by $Q_{SI} = D_{NI} A_C \varepsilon$, where A_C is solar collector area and ε is the solar collector efficiency. Based on the above, the monthly cooling load for the building is shown in Figure 4. The conservation equations for each equipment in the cycle was developed and was basis for system simulations.

IV. CASE STUDY OF A HIGH RISE APARTMENT BLOCK

A. Plant Sizing

The candidate apartment block is located in Ahmedabad, (23.052º N 72.539º E), India. It has 102 residences each of 400 m^2 area over 13 floors. The total wall area of the building and fenestration area of the wall facing to the sun were estimated as 3333 m^2 and 24 m^2, respectively. Meteorological data was obtained from *Solcast API Toolkit* [9, 10]. One representative day (with highest DBT) for each month was selected for which cooling load calculations were performed.

Each apartment in the building is fitted with split air conditioners of 1.5 TR capacity, and the total installed AC capacity is 120 TR which is adequate to meet the cooling demand of all the apartments, and this is taken as the base case for design of the DCS. Accordingly, the DCS is based on a VAM chiller of 120 TR which is hot water fired double effect type with COP of 1.4; its cooling tower for heat rejection is 184 T.

A solar array that heats a thermic fluid has been sized with water as the thermic fluid which is pressurized and not allowed to boil. For steady state operation of the chiller plant, the required mass flow rate of hot water in the collectors is calculated as 4.91 kg/s. Based on a temperature rise from 165 °C to 180 °C during peak hours, the number of parallel collector lines is 10 each 47 m long (based on manufacturers' data). Allowing for some spare capacity, the required parabolic trough collector area is 1300 m^2. From manufacturers' data a collector unit length is 4.3 m with 2.5 m aperture width for an aperture area of 10.4 m^2 [11]. Allowing for access space between consecutive lines, the required land area works out to 3500 m^2.

For steady state operation, a 120 TR VAM requires about 85 TR heat supply rate. Against this, the peak heating rate from the solar collectors is 192 TR. Figure 5 shows the hourly variation in availability versus requirement of heat energy on a typical day in June.

The total heat output during solar hours throughout the day from the solar field is 1739 TR-hours of heating and the total heating demand in chiller plant during same solar hours is 931 TR-hours. So the required hot thermic fluid tank should have storage capacity of 808 TR-hours to meet heating demand in non-solar hours; this works out to a capacity of 162 m^3 (e.g. 5.5 m diameter x 6.12 m high). During peak demand hours, the cooling demand is 1388 TR-hours whereas the maximum cooling demand supplied by VAM is 1080 TR-hours. So, the required chilled water tank should have storage capacity of 308 TR-hours; typical capacity 132 m^3 (5.5 m diameter x 5.53 m high).

The integrated solar-based VAM DCS of Figure 2 has three sub-systems, viz., as a combination of three sub-systems, viz., (a) solar farm, (b) chiller plant, and (c) consumers, and these could be geographically located near one another or at separated locations.

B. System Operation

In the apartment block, a piping system will have to be provided to each consumer (irrespective of the number of FCUs) connect to each fan coil unit in a residential unit (Figure 1).

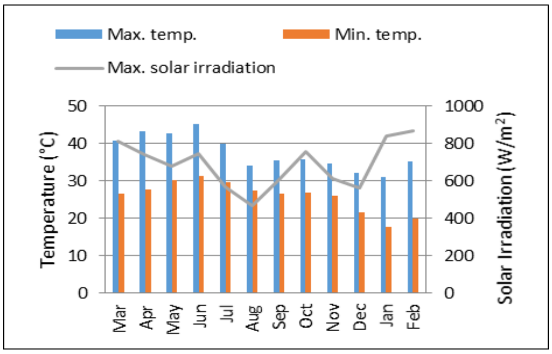

Figure 3 Monthly maximum and minimum DBT and maximum solar irradiation

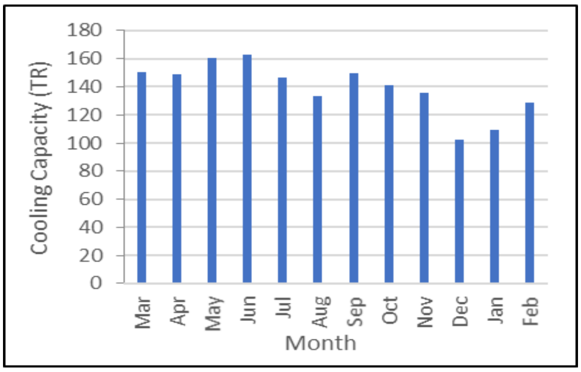

Figure 4 Month-wise variation of cooling load of the building

Given the variations in solar availability, weather conditions and consumer demand, different operational strategies need to be evolved. On clear days, the variation of availability and requirement of solar thermal energy is as in Figure 5. Early mornings, solar irradiation and consumer demand are minimal, hence, the VAM is operated at part capacity while drawing stored hot thermic fluid. During peak solar hours, the available solar energy exceeds VAM heating requirement which meets the full demand of the VAM and also stores hot thermic fluid in the its storage tank. Simultaneously, the chilled water is also drawn down. During cloudy days solar irradiation is very less or sometimes negligible. In such conditions, hot thermic fluid will have to be provided from an alternate heat source, such as, gas-fired auxiliary boiler.

A DCS would cater to the needs of a variety of consumers whose demand can have profiles with durations of 24, 8, and 12-14 hours.

V. COMPARISON OF VAM- AND VCR-BASED DCS

A competing technology of the proposed system is the replacement of VAM and solar collector by VCR chiller. The energy savings are compared with the equivalent system which consists of one VCR chiller of the same capacity. The annual power consumption for both VAM based system and VCR based system is calculated assuming 24-hour operation for all days.

Based on this relation, the annual electrical consumption of VAM based district cooling system is 167,270 kWh while for the VCR based district cooling system, it is 681,600 kWh per annum. For unitary split systems in each residence, the electricity consumed for same cooling effect is 790,732 kWh per annum. If the solar farm land of 3500 m^2 were to be used for generating electricity via SPV, then the annual generation will be 273,000 kWh [12].

The carbon footprint is calculated from electricity consumed on the basis of CO2 emission per kWh of electricity generation. According to country specific electricity factors, for India CO2 emission per kWh of electricity generation is 0.74 kg. So the annual carbon emission from VAM based district cooling system is 123,780 kg while for the VCR based district cooling system it is 504,384 kg per annum. For the existing system with unitary split air conditioners, it is 585,142 kg per annum.

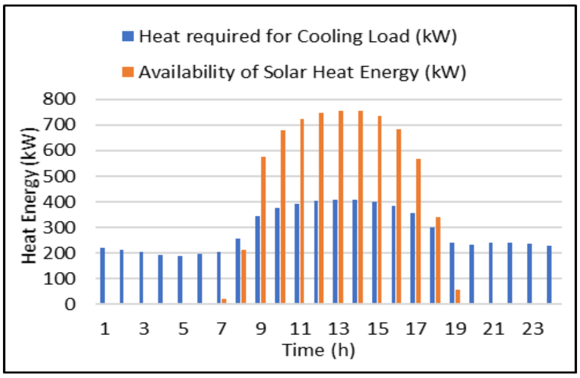

Figure 5 Solar energy availability and VAM heat requirement for a typical day in June.

Therefore, a solar VAM DCS has almost a 79 % smaller carbon footprint than the present practice of unitary split ACs.

VI. ECONOMIC ANALYSIS

The economic feasibility is based on capital and operating costs from which the payback periods, IRR and NPV are calculated. This analysis is based on the enterprise perspective and the calculation and analysis involve comparison with existing alternatives, and implications from the user's viewpoint.

A. *Methodology*

To establish the economic feasibility of the VAM-DCS system, the capital and operating costs of both VAM and VCR have been calculated. The asset prices are determined from discussions with various manufacturers.

B. *Cost basis:*

All the costs have been obtained from vendors, suppliers, and from experts in the respective services, and are indexed to 2020 prices with the inflation rate of 5 % per annum for equipment, raw material, office overhead, electricity charges, and maintenance. Operating cost is calculated for 20 years.

(i) Land: In the analysis it is assumed that the land is already available, and no expenses are incurred for its acquisition. However, if the client doesn't have land or terrace space then it could be leased or purchased outright; in Ahmedabad, the current average leasing rate is about Rs. 92 per sq. meter. (ii) Building and structural**:** The control room size is 50 m^2 which will house all the machines and control units. The construction costs are taken as Rs.12,000 per m^2. Costs of supporting structures for collectors are taken at 5 % of the capital cost. (iii) Parabolic trough collector: Each collector panel is 4.3 m long and 2.5 m wide and 120 units are needed; unit cost is Rs 18000. (iv) Storage tanks and cooling tower: The unit cost of hot and cold thermic fluid storage tanks is around Rs 3.5 million and that for warm and chilled water tanks is approx. Rs 3 million. (v) Instrumentation and controls: The cost of instrumentation components is considered at 2 % of the total capital cost of plant machinery, buildings and other structures, tanks, pumps, cooling tower, and piping and valves. (vi) Design and consultancy services: These charges are taken as Rs 50000. (vii) Transportation and logistics: The transportation cost is calculated by considering the weight, and distance between vendors and the site via surface transport. (viii) Installation cost: The installations will be done by a team of skilled workers at a total cost of Rs 1.2 lacs over 2 months, however the VCR-DCS does not required separate installation cost. (ix) Electrical charges: Based on the prevailing tariff structure from a local vendor[13], fixed electricity charges are estimated at Rs. 1080 per meter annually. The plant is considered to be operating 24 hours every day. The per-unit charge of electricity is taken at Rs. 4.5. (x) Thermic fluid and water costs: Initial charging of chilled water circuit (soft water) is estimated at Rs. 24 per 1000 liter. (xi) Maintenance and staff salary: Maintenance cost per year is considered at 0.5 % of the capital cost. The wages for operating, and maintenance staff have been considered at Rs. 12,000, 7,000, and 4,000 per month, respectively, for the operator, security, and cleaner, with an increment of 5 % every year. The maintenance cost is increased every year with an inflation rate of 5 %. (xii) Piping: The cost of insulated piping is taken as Rs 2250 per meter. Piping and valve cost are taken as 5 % of plant & structure, tanks, and pumps. (xiii) Fan coil unit (FCU): The fan coil unit cost is taken as Rs 15,000 per 1.5 TR unit. (xiv) Plant commissioning: Commissioning is a specialized activity, and its costs are estimated at 7 % of the total capital cost.

C. *Capital cost*

Based on the above unit costs, the capital cost comparison between VCR-based DCS and VAM-based DCS is given in ***Table 1*** below as per [14].

Table 1 Capital cost comparisons between VCR and VAM systems

	Particulars	**VAM DCS (Cost,000 ₹)**	**VCR DCS (Cost,000 ₹)**
A	Plant, machinery, building and structure	7,623	5,600
B	Tanks	13,182	6,179.972
C	Pumps	280	120
D	Instrumentation, Control and Piping	2205	1,807.657
E	HVAC Designer	50	50
F	Transportation and Logistics	66	25.6
G	Transit Insurance	25.3	3.7
H	Manpower	121.8	-
	Capital cost	**23,503.571**	**13,780.929**
	7 % Commission from sale of plant	**1,645.250**	**964.665**
	TOTAL CAPITAL COST	**25,148.821**	**14,745.595**

D. *Depreciation schedule*

A depreciation schedule is calculated by making four blocks of assets, viz.., General, Tanks, Pumps, Instrumentation Control and Piping. Depreciation is calculated for 20 years, the rate of depreciation is 15 % annually, and 30 % for others based on which a detailed schedule has been prepared as per [15].

E. *Operating Expenses*

The annual operating expense is calculated for 20 years taking into account a 5 % inflation rate every year. ***Table 2*** represent the operating expense. Maintenance is a sinking fund that is needed for the maintenance of assets and this is taken as 0.5 % of capital cost for the first year and 5 % for the subsequent years; a 5 % inflation rate is considered. The operating cost comparison between VCR-based and VAM-based DCS is shown in ***Table 2***.

Table 2 Operating Cost of VAM and VCR DCS

	Particular		**Operating Cost DCS (Cost in, 000 Rs)**		
	No of years		**1**	**10**	**20**
A	Water for circulation	VAM	33.6	52.12	84.91
		VCS	33.6	52.12	84.91
B	Office (management) overheads	VAM	588	912.18	1485.85
		VCS	588	912.18	1485.85
C	Electricity charges (Pump, VAM, cooling tower)	VAM	940.89	1459.64	2377.6
		VCS	3834	5947.79	9688.33
D	Maintenance (@ 0.5% of capital cost)	VAM	125.744	195.07	317.75
		VCS	73.73	114.38	186.31
E	Tax Savings on Depreciation	VAM	-1131.82	-262.15	-51.61
		VCS	-663.55	-153.69	-30.26
F	**Total Annual Operating Expense**	**VAM**	**556.42**	**2356.87**	**4214.488**
		VCS	**3865.78**	**6872.784**	**11415.13**

F. *Other Comparators*

Present value of the cash inflow for 20 years is obtained by multiplying it with the discount rate of 10 % or with the relation $PV = (1 + i)n$ where 'i' and 'n' are 10% and 20 years, respectively. The payback period is calculated through discounted payback period which is $y + abs(n)/p$ where y is the period preceding the period in which the cumulative cash flow turns positive, p is discounted cash flow during the period after y, and abs(n) is the absolute value of the difference between initial capital outlay and the value preceding the period in which the cumulative cash flow turns positive. According to Knight [16], the net present value (NPV) is the present value of the cash flow at the required rate of return and calculated as = PV(cash inflow) – PV(Cash outflow). The Internal Rate of Return is used as basis of profitability of the investments made. IRR accounts for fluctuations in the investment made. It is the discount rate at which the NPV of a project is zero, and is given by,

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1 + r)^t}$$

G. *Unitary split AC costs*

The costs of the existing unitary split ACs in the apartment tower are derived after consulting various local vendors. The cost mentioned below is for per unit. However, here, the total number of units is taken as 80.

The economic analysis of the split AC system includes capital of Rs 65990, installation cost of Rs 5000, maintenance cost of Rs 4000, and electricity cost of Rs 44500[per month] respectively. The capital and installation cost are a one-time cost whereas the maintenance and electricity costs are recurring costs. This cost changes every year, having an average 10 % increase every year. Here, the diversity factor of split A/C (1.5 TR) is taken as 0.8 [17].

VII. VIABILITY ANALYSIS

A. *Comparison of VAM DCS and VCR DCS*

The VAM system has higher capital investments, but its annual operating cost is very low. The capital cost of VAM is around 41 % more than the capital cost of VCR. On the other hand, annually VAM saves approximately 63 % in operating costs. Discounted Payback period through cost savings is about 11 years 3 months, whereas discounted payback period using subsidy received is about 7 years 1 month. As a result, the client recovers all the capital investments within a maximum period of 11 years and 3 months. The client could reap the benefits of the plant for 9 more years with a nominal operating cost. A subsidy of Rs. 7.5 million is provided by the UNDP-GEF project. When the subsidy is taken into consideration the investment falls by a similar amount, resulting in decreasing the discounted payback period and bringing it down to 7 years and 1 month. Although VCR has less capital cost in long run its operating cost is very high as compared to VAM. Moreover, the IRR without subsidy is 15 % and with subsidy comes out to be 22 %.

B. *Comparison of VAM existing unitary split AC system*

The capital cost of VAM is around 361 % more than the capital cost of a split air conditioning system. On the other hand, annually VAM saves approximately 62 % in operating costs.The payback period through cost savings is about 10 years 10 months, whereas the payback period using subsidy received is about 7 years 9 months. A subsidy of Rs. 7.5 million is provided by UNDP- GEF project. As a result, the client recovers all the capital investments within a maximum period of 10 years and 10 months.

VIII. CONCLUSIONS

This study has shown that a solar-based VAM district cooling system is technically and economically feasible and in many ways superior to a similar VCR-based DCS and existing unitary split AC systems. A case study of a residential tower is presented where capital investment of the VAM-based system is greater by 58 % compared to its VCR counterpart, and 361 % more compared to split air conditioners. The cost-saving in operation and maintenance of VAM is around 61 % lower than a VCR DCS, and 62 % lower than split AC decentralized installations. The carbon footprint of VAM DCS is 75 lower than VCR DCS and 78 % lower than unitary split AC systems and would be eligible for carbon credits. At a practical implementation and operational level, VAM DCS has several challenges which would have to be addressed, however, the potential carbon savings are very significant which is the need of the hour to slow down climate change.

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